



Greenhouse gas emissions reduction in different economic sectors: Mitigation measures, health co-benefits, knowledge gaps, and policy implications[☆]

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ABSTRACT

To date, greenhouse gas (GHG) emissions, mitigation strategies and the accompanying health co-benefits in different economic sectors have not been fully investigated. The purpose of this paper is to review comprehensively the evidence on GHG mitigation measures and the related health co-benefits, identify knowledge gaps, and provide recommendations to promote further development and implementation of climate change response policies. Evidence on GHG emissions, abatement measures and related health co-benefits has been observed at regional, national and global levels, involving both low- and high-income societies. GHG mitigation actions have mainly been taken in five sectors: energy generation, transport, food and agriculture, household and industry, consistent with the main sources of GHG emissions. GHGs and air pollutants to a large extent stem from the same sources and are inseparable in terms of their atmospheric evolution and effects on ecosystem; thus, GHG reductions are usually, although not always, estimated to have cost effective co-benefits for public health. Some integrated mitigation strategies involving multiple sectors, which tend to create greater health benefits. The pros and cons of different mitigation measures, issues with existing knowledge, priorities for research, and potential policy implications were also discussed. Findings from this study can play a role not only in motivating large GHG emitters to make decisive changes in GHG emissions, but also in facilitating cooperation at international, national and regional levels, to promote GHG mitigation policies that protect public health from climate change and air pollution simultaneously.

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1. Introduction

According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), climate change is unequivocal, and during the period 1880 to 2012, there was a warming of 0.85 °C in the global average surface temperature (Pachauri et al., 2014b; Stocker et al., 2013). Without further mitigation actions, the average temperature may rise by 2.6–4.8 °C by the end of this century (Watts et al., 2015). The health of human beings is sensitive to shifts in weather patterns and other changes of climate systems (e.g., temperature, precipitation and extreme weather events) (Smith et al., 2014; Woodward et al., 2014). Thus, climate change, both directly and indirectly, can and has already started to damage human health through various pathways, and is projected to lead to increasingly adverse impacts in future (Fig. 1) (Field et al., 2014; McMichael et al., 2006; Pachauri et al., 2014b; Watts et al., 2015; Woodward et al., 2014). In 2000, the World Health Organization (WHO) estimated that climate change could cause more than 150,000 deaths and 5.5 million disability-adjusted life years (DALYs) lost worldwide (McMichael et al., 2004). Benefits from social and economic development may offset, to a certain degree, the adverse influences of climate change on human populations, but cannot eliminate them. For instance, considering only a subset of the associated health risks—well understood impacts—and assuming continued progress in socioeconomic development and health protection, climate change is still projected to have substantial impacts on future public health (Chan, 2015; Hales et al., 2014). In 2014, WHO estimated an additional approximately 250,000 deaths due to climate change annually between 2030 and 2050. WHO suggested that their assessments represent a conservative prediction of the overall effects of climate change, because they omit several important causal pathways (Hales et al., 2014; Watts et al., 2015). If no further climate change mitigation actions are undertaken, the combined effects of the

selected impacts on global annual gross domestic product (GDP) are expected to rise over time to likely levels of 1.0%–3.3% by 2060, with the largest negative economic consequences suffered by regions in Africa and Asia (Organization for Economic Co-operation and Development, 2015). Climate change has been described as the biggest global health threat of the 21st century (Costello et al., 2009).

Anthropogenic greenhouse gas (GHG) emissions, primarily from human activity-related energy generation, transport, food and agriculture, household and industrial processes, are considered as the main driver of climate change (Pachauri et al., 2014b; Stocker et al., 2013). In order to hold the increase in global temperature to less than 2 °C relative to pre-industrial levels to avoid the risk of potentially catastrophic climate change impacts, total anthropogenic carbon dioxide (CO₂) emissions were required to be kept below 2900 billion tonnes (Gt) by the end of this century (Watts et al., 2015; Whitmee et al., 2015). However, in the years 2003–2011, an average global annual emissions growth rate of 3% per year was observed, whereas the growth figure over the 1980–2002 period was 1.2% annually (Olivier et al., 2015; Netherlands Environmental Assessment Agency, 2007). In 2014, emissions from the combustion of fossil fuels and industrial processes totaled 35.7 Gt CO₂ (Fig. 2), with current trends expected to exceed the required emissions target over the next 15–30 years (Olivier et al., 2015; Watts et al., 2015).

In terms of the potential expensive and far-reaching health consequences of climate change, as well as the likely increasing GHG emission trends, urgent and substantial actions are needed to reduce GHG emissions and thus stabilize the global climate system before the extent and magnitude become more dangerous. It has been suggested that tackling climate change could be the greatest global health opportunity in the 21st century (Watts et al., 2015). International climate change negotiations are in progress regarding further GHG reductions and increasing the number of countries

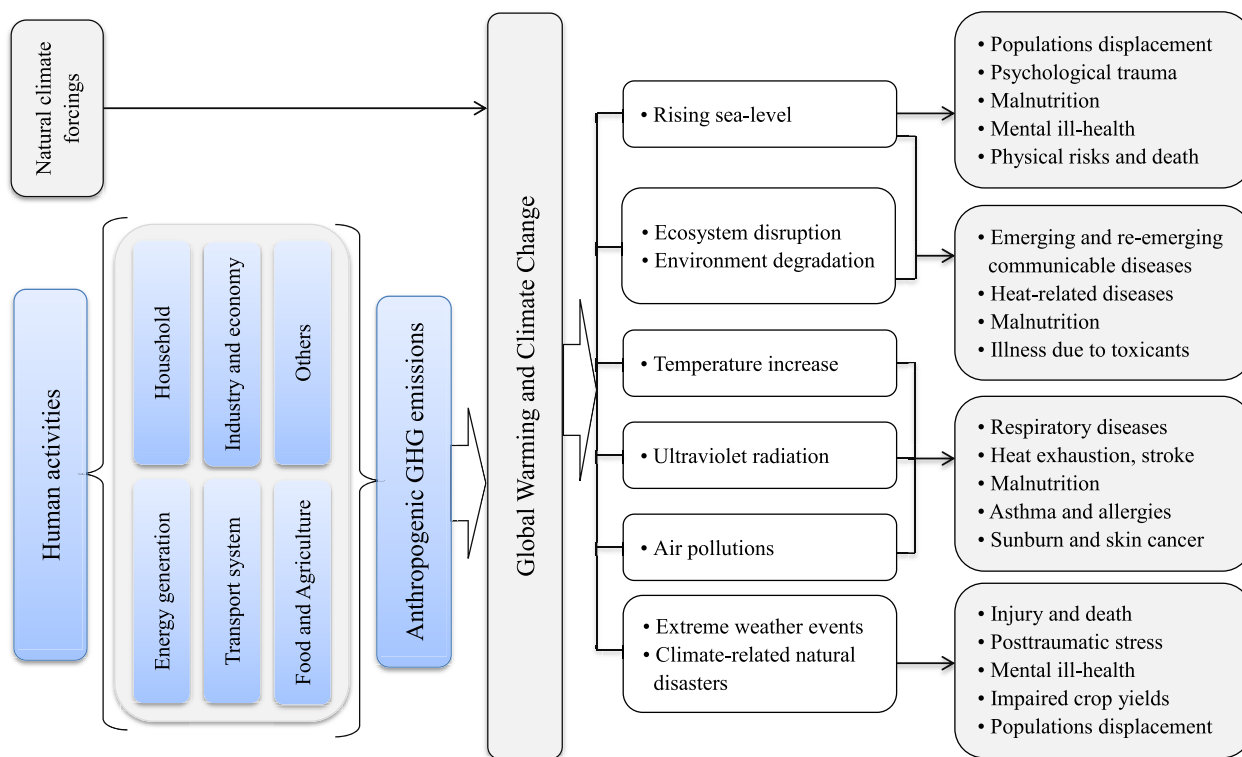


Fig. 1. Main drivers of climate change and potential pathways through which climate change impacts public health.

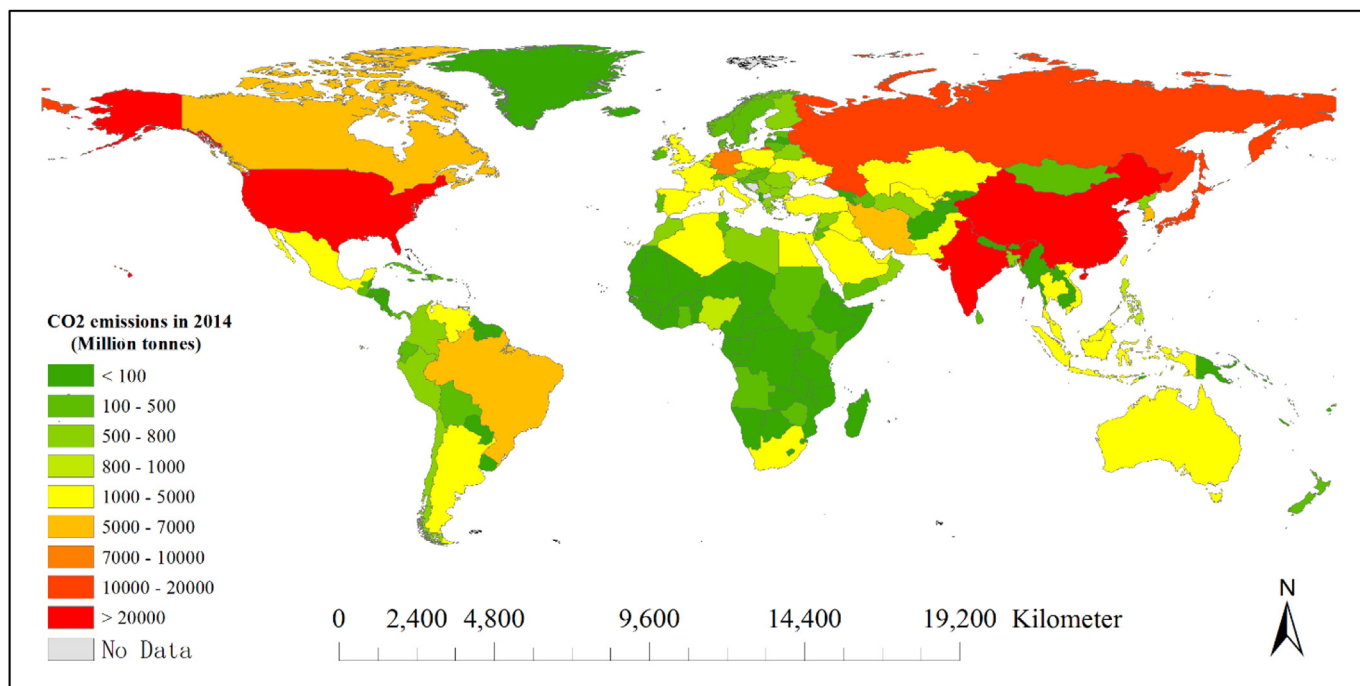


Fig. 2. Global CO₂ emissions from fossil fuel use and cement production in 2014. Data source: EDGARv4.3, EC-JRC/PBL_EDGAR version 4.3. FT2014 (Jos G.J. Olivier et al., 2015). <http://edgar.jrc.ec.europa.eu/>.

with binding commitments to reduce GHG emissions to meet the 2 °C goal, consistent with science and on the basis of equity (International Energy Agency, 2015; Chae and Park, 2011). For example, during the United Nations Framework Convention on Climate Change (UNFCCC) 21st session of the Conference of the Parties (COP21), for the first time over the past 20 years of inter-governmental talks, universal agreements on climate change and mitigation actions were achieved (Rhodes, 2016; Robbins, 2016). Of the worldwide GHG reduction efforts, active participation and decisive actions of developing countries are essential to limit the increase in GHG concentrations and prevent dangerous anthropogenic interference with the climate system (International Energy Agency, 2015; Pachauri et al., 2014b). However, developing nations are concentrating so much on economic development, air quality improvement and poverty reduction, that they have limited economic resources and a low priority on the political agenda to tackle the challenges posed by GHG emissions and climate change (Barros et al., 2014; Chae and Park, 2011; Field et al., 2014; Watts et al., 2017b). In light of the “common but shared responsibility” principle of UNFCCC, the issue of how to balance countries’ rights to sustainable development and economic growth—especially the rights of developing nations—with enforceable GHG emissions reduction, may be the key challenge of ambitious global mitigation action (Baer et al., 2010; Watts et al., 2015; Xu and Ramanathan, 2017).

An opportunity to help address this challenge, provide a political bridge across the development gap, and bring low- and high-income countries together irrespective of national boundaries to achieve the climate change mitigation targets, lies in the public health co-benefits of GHG abatement strategies (Gao et al., 2018; Haines et al., 2009; Patz et al., 2014; Watts et al., 2015). According to the IPCC, mitigation strategies not only act to curb the emissions of climate-warming pollutants (mainly GHGs), but also, if well be chosen and implemented, deliver substantial simultaneous improvements in public health, independent of the effects on climate change, with most of these impacts being beneficial (Field et al.,

2014; Pachauri et al., 2014b; Smith et al., 2014). One of the mechanisms for these so-called “health co-benefits” of mitigation measures is that GHGs and air pollutants to a large extent stem from the same sources and are inseparable in terms of their atmospheric evolution and effects on ecosystems and human beings (Fig. 3) (Aunan et al., 2006; Chae and Park, 2011; Lelieveld et al., 2015; Pachauri et al., 2014b; Sofiev et al., 2018; Stocker et al., 2013). Moreover, some air pollutants such as black carbon (BC) and ozone (O₃) are also greenhouse pollutants (climate-warming agents) with even higher radiative forcing (RF) per unit than CO₂ (Smith et al., 2009; Stocker et al., 2013).

These co-benefits from simultaneously tackling climate change and air pollution and improving additional public health may make GHG mitigation strategies more attractive to stakeholders, help to achieve convergence of mitigation schedules between low- and high-income countries, and provide extra incentives to motivate efforts and policies to put these schedules into practice (Cifuentes et al., 2001; Haines et al., 2009; Patz et al., 2014; Watts et al., 2015, 2017b). However, to date, the evidence of GHG emissions, mitigation strategies and the corresponding health co-benefits in different social or economic sectors has not been extensively summarized and discussed. Given the roles mentioned of the health co-benefits in relation to GHG abatement, a thorough understanding of this issue is of particular strategic significance. Thus, with a view to filling some of the knowledge gaps on the topic of GHG emissions and related mitigation measures, the main purpose of this study is to synthesize comprehensively the evidence of current GHG emission situations, mitigation strategies and the accompanying health co-benefits in different economic sectors, identify existing knowledge gaps, and then discuss potential policy implications. To the best of our knowledge, this is the first comprehensive account of this particular topic related to GHG emissions, and we hope the findings will help improve the further development and implementation of climate change response policies.

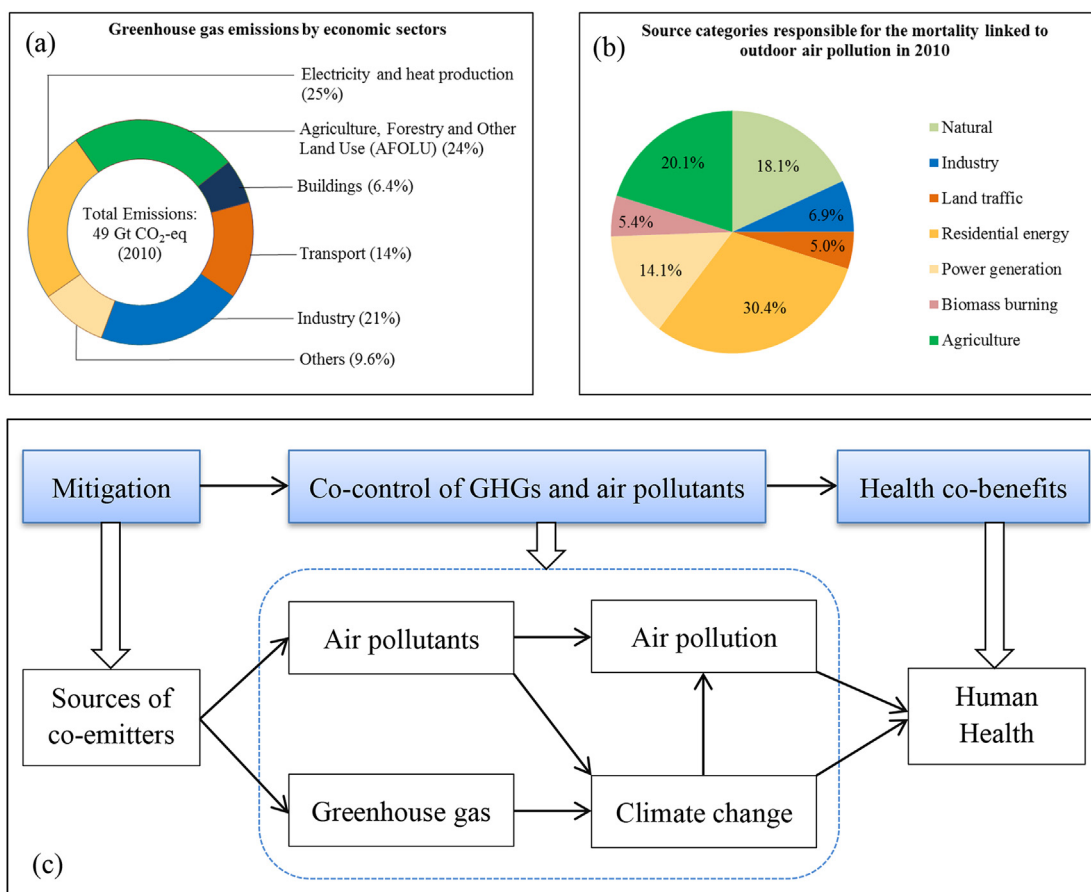


Fig. 3. Sources of greenhouse gases (GHGs) and air pollutants, and potential pathways of GHG mitigation strategies bring about health co-benefits. (a), The shares of direct GHGs emissions (in percentage of total anthropogenic GHGs emissions) from five economic sectors in 2010 (Data source from IPCC AR5 (Stocker et al., 2013)). (b), Seven source categories that responsible for the largest impact on premature mortality (for subpopulations of <5 and ≥ 30 years old) associated with PM_{2.5} and O₃ related diseases in 2010 (Data source from report of (Lelieveld et al., 2015)). (c), Potential mechanisms and pathways through which GHG reductions result in public health co-benefits.

2. GHG emissions, mitigation strategies, and corresponding health co-benefits

To date, the evidence of GHG emissions, abatement measures and related public health co-benefits have been observed at regional, national and global levels, involving both low- and high-income societies (Chae and Park, 2011; Cheng and Berry, 2013; Haines et al., 2009; Markandya et al., 2009; Shindell et al., 2012; Xia et al., 2015). Although to some extent there are intersections and overlaps, GHG mitigation actions have been taken or discussed mainly in five sectors: energy generation, transport systems, food and agriculture, household, and industrial and economic processes, nearly consistent with the main sources of GHGs (Fig. 3) (Cheng and Berry, 2013; Haines et al., 2009; Pachauri et al., 2014b; Patz et al., 2014). In addition, some integrated mitigation strategies involving various sectors (e.g., energy, transport, household, forestry, or waste treatment) and their health impacts were also investigated in the scientific literature (Anenberg et al., 2012; Rafaj et al., 2013; Sabel et al., 2016; West et al., 2012). In the following section, we will present our findings according to the five main sectors, plus a brief discussion of some others.

2.1. Energy generation

According to the report of *Energy Technology Perspectives* (2015) from International energy agency (IEA, <http://www.iea.org/etp/>), the energy sector alone was responsible for around two-thirds of

global CO₂ emissions in 2012, and CO₂ from energy accounts for about three-quarters of the anthropogenic GHG emissions for Annex I (industrialized) countries (International Energy Agency, 2015). In the energy sector, the major health threats primarily result from air pollution, GHG emissions, occupational hazards, and the risks of sporadic large-scale accidents, which together cause substantially more environment-mediated morbidity and mortality worldwide than any other sector (Prüss-Ustün et al., 2004; Smith and Haigler, 2008). For instance, as the largest sources of anthropogenic GHGs, combustion of fuels, especially fossil-fuel use, causes air pollution (e.g., PM, NO_x and SO₂), contributing to mortality and morbidity (Cifuentes et al., 2001; Smith and Haigler, 2008), with developing countries being more affected due to the more extensive use of coal and the generally less stringent emission control requirements. It has been estimated that approximately 3.2 million premature deaths globally or about 3% of the global disease burden are attributable to ambient particulate pollution, and the WHO has ranked air pollution as one of the top 10 causes of global disease burden (Cifuentes et al., 2001; Forouzanfar et al., 2016; Lim et al., 2013; Smith et al., 2014). Considering that the sources of GHGs and air pollutants in the energy sector are largely the same, what should be highlighted is that innovations across a portfolio of clean energy technologies, including decarbonization of energy generation, improvements in energy efficiency, and switching of energy structure, have large potential for climate change mitigation, air pollution control, and ancillary health gains (Fig. 4).

Decarbonization in energy production can cut down emissions

of GHGs and air pollutants at the same time. Crawford-Brown et al. modeled one such scenario for Mexico for 2050 which involved the reduction of CO₂ emissions through climate change policies. With respect to the reference case, the scenario brings a 77% reduction in CO₂ emissions, accompanied by an encouraging decrease in emissions of air pollutants (Crawford-Brown et al., 2012). Another clean production technology, namely carbon capture and storage (CCS), has been described as the only instrument available to manage GHG emissions from large-scale fossil fuel usage in power generation, industry and transportation (IEA, 2009; from <http://www.iea.org/publications/>). CCS encompasses a number of different post- and pre-combustion capture approaches to capture, transport and storage of CO₂, and is promoted as a “bridging” technology which can both smooth the transition towards a future sustainable energy system, as well as allow continued use of today’s fossil fuels based energy in the near future (Tzanidakis et al., 2013; Veltman et al., 2010). However, although widespread deployment of CCS will offer a promising technological pathway to reduce CO₂ emissions while allow continued reliance on fossil fuel, questions arise regarding the wider adverse impacts on environment, ecosystem and human health (Veltman et al., 2010; Zhang et al., 2013b). For instance, as the only commercially available approach nowadays to capture CO₂ from dilute atmospheric pressure gas, it is reported that amine-based scrubbing could result in a 10-fold increase in toxic impact on freshwater ecosystems (Veltman et al., 2010). Another study from the UK also indicated that implementation of CCS on existing power plants can lead to increases in NO_x, NH₃ and PM emissions from the stack, and deteriorate the local air quality as well as threat public health (Tzanidakis et al., 2013). Thus, present CCS technology may not have been developed consummate enough to fit for widespread application, and even if it did bring climate benefits, these may be offset, to a certain extent, by its side-effects on air quality (Markandya et al., 2009; Tzanidakis et al., 2013; Zhang et al., 2013a). Here is one example of a general point: what works for managing climate change risk is not always aligned with what protects and promotes human health. In order to maximize the future environment and health benefits of CCS and avoid any unintended negative effects, further research is needed.

According to the IEA, improvement in energy efficiency is an emerging policy priority for many countries worldwide, since it is considered to be a highly cost effective and readily available measure that can provide win–win situations for both air pollution control and GHG emissions abatement (Apsimon et al., 2009; International Energy Agency, 2014). For example, a study from China estimated that gains in energy efficiency had effectively

reduced national CO₂ emissions by 50–60% (Peters et al., 2007). Others have claimed that the promotion of energy efficiency may lead to substantial air pollution reductions and health benefits, provided that the gains in efficiency are translated into reduced consumption (Chen et al., 2013; Lee and Van de Meene, 2013; Yang et al., 2013). Thus, taking the co-control of GHGs and pollutant emissions into account along with the corresponding health benefits, energy efficiency improvement should be given greater emphasis by all countries, and could be considered as a vital strategic choice to improve local air quality and simultaneously mitigate global climate change (International Energy Agency, 2014; Yang et al., 2013).

Increasing energy demand and concerns over energy security, air pollution and climate change have led many countries to focus on shifting their energy structures, mainly through increasing lower-emission forms of energy like natural gas and nuclear, and developing renewables such as wind, solar and biofuel energy (Ma et al., 2013; Watts et al., 2017a; Xue et al., 2015). For example, it has been estimated that, per unit of electricity generated, the emissions of CO₂, NO_x and SO₂ from natural gas-fired power plants are 50%, below 30%, and 1% of those from typical coal-fired ones, respectively, largely owing to the lower emission rate and higher energy efficiency of natural gas during the combustion process (Liu et al., 2013). Renewable energy alternatives like geothermal, solar and biofuel energy could all bring benefits for GHG mitigation, air quality and public health, but wind energy is favored by many. Despite potential terrestrial and aerial impacts on wildlife (e.g., habitat loss, fragmentation and avoidance), wind energy has significant advantages in terms of reductions in CO₂ emissions, air pollutants and water demand for energy generation, as well as lower costs in installation and generation (Kiesecker et al., 2011; Kunz et al., 2007; Ma et al., 2013; West et al., 2013; Zhai et al., 2011). One study reported that for the same amount of power generation, wind energy only released 1/40 of the total CO₂ emissions from a coal power system, which is equal to a 97.48% reduction in CO₂ emissions; and wind can achieve also reductions of 80.38%, 57.31%, and 30.91% in SO₂, NO_x and PM₁₀ emissions, respectively (Xue et al., 2015).

While actions in other sectors can help to conduct ambitious global climate mitigation, major changes in energy production and use are urgently needed, given that this sector makes the largest worldwide contributions to anthropogenic GHG emissions (Smith and Haigler, 2008; Solomon, 2007). Markandya and colleagues estimated the health co-benefits of strategies associated with electricity generation to reduce GHG emissions, and the results

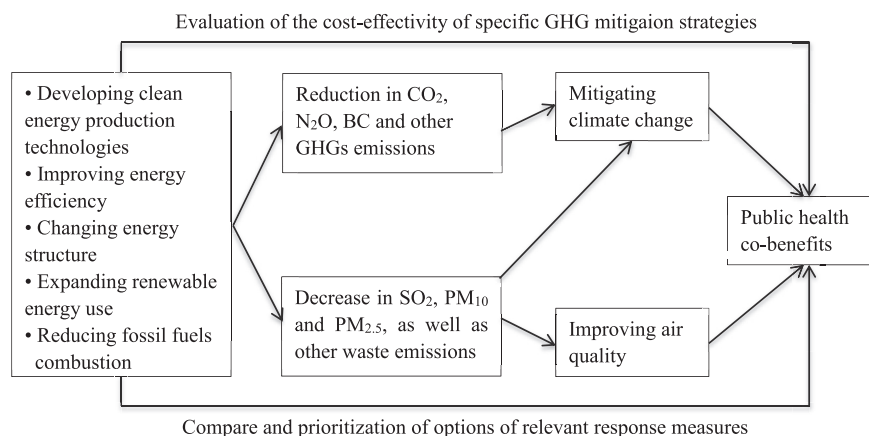


Fig. 4. GHG mitigation measures and potential health co-benefits in energy sector.

indicated that compared with business-as-usual (BAU), with a 50% reduction in GHG by 2030, the health gains in the European Union, China and India would be approximately 100, 500 and 1500 life-years per million people, respectively, which would greatly offset the costs of measures conduction, especially in India where pollution is serious and mitigation costs are relatively low (Markandya et al., 2009). Relative to the reference case in 2100, West et al. reported that global GHG mitigation measures involving decrease in fossil fuel use and energy demand, and increase in forest cover, biofuels use and CCS, could curb global temperature increase to about 2.3 °C and avoid 2.2 ± 0.8 million premature deaths because of reductions in PM_{2.5} and O₃ (West et al., 2013). Thus, assessing the benefits of abatement measures in the energy sector can play a role in helping to overcome the present hurdles and motivating GHG mitigation actions throughout the developed and developing world.

2.2. Transport system

The transport sector currently accounts for nearly 60% of global oil demand and 30% of the world's total delivered energy, and has been described as the second largest energy consumer after industry (Atabani et al., 2011). Motor vehicles such as cars, buses and trucks, are increasingly important contributors to global anthropogenic GHG emissions. It is estimated that 23% of world energy-related GHG emissions can be attributed to transport systems and 74% of these emissions come from land transport (cars, buses and trucks) (Kahn Ribeiro et al., 2007; Woodcock et al., 2009). GHG emissions from transport systems are predicted to increase rapidly worldwide and may be 80% higher than their 2007 levels by 2030 (Kahn Ribeiro et al., 2007; Woodcock et al., 2009; Xia et al., 2013). In addition, traffic-related pollutants such as PM and NO_x also have considerable and direct impacts on public health in both developed and developing countries (Begg et al., 2007; Sofiev et al., 2018; Yim and Barrett, 2012). By vehicle type, it is estimated that the relative contributions in PM_{2.5} concentrations of trucks, buses, motorbikes and cars are 69%, 23%, 5% and 3%, respectively, and the contribution of transport system to total PM_{2.5} is about 60% (Sa et al., 2017). Globally, in addition to emit huge amount of SO₂ and PM, heavy-duty trucks also account for the largest share of on-road vehicles' NO_x emissions (Takeshita, 2012). Thus, increase in active travel (e.g., walking and cycling), decreased use of motor vehicles, production of lower-emission and efficiency-enhancing motor vehicles (cars, buses and trucks), and promoting research and development of cost-effective low-carbon alternatives to diesel heavy-duty trucks have the potential to benefit climate, air quality and public health (Fig. 5).

Motor vehicles are a source of various toxic air pollutants (e.g., PM, NO_x, VOCs, and CO), and some of the pollutants are also climate-active agents, such as NO_x and BC. Considering the rapid expansion of vehicle use in developing metropolitan areas around the world, transport system has become a major contributor to urban air pollution and GHG emissions (Kelly et al., 2017; Li and Crawford-Brown, 2011; Woodcock et al., 2009). NO_x emissions in Shanghai for example, owing to the expansion of road transport, are projected to increase by 60–70% by 2020 (Changhong et al., 2006). Given that the frequent co-location of high concentrations of traffic-related air pollutants, large populations and congested motor vehicles are common features in many areas worldwide, it is no surprise that the health co-benefits associated with GHG mitigation measures targeting transport systems (e.g., decreased use of private motor vehicles and increased penetration of lower-emission and efficiency-enhancing cars, buses and especially heavy-duty trucks) have been suggested by scientific evidence; and transport system is frequently regarded as the key to sustainable urban renovation

(Anenberg et al., 2011; Chong et al., 2014; Kwan et al., 2017; Li and Crawford-Brown, 2011; Mao et al., 2012; Sa et al., 2017; Xia et al., 2013). For instance, according to Perez et al., in addition to stabilized or reduced CO₂ emissions, for the scenario that assumed a strict PM emissions standard in diesel cars and all planned transport measures in Basel, Switzerland, 3% of premature deaths could be avoided due to PM_{2.5} exposure reduction, and a strong support to electric vehicles diffusion would have the largest health effectiveness (Perez et al., 2015).

Active travel, including walking, cycling and using public transport (which nearly always includes a component of walking), is the suggested best means of reducing GHG emissions with nearly “zero-pollutant” for short city trips (Lee and Van de Meene, 2013; Maizlish et al., 2017; Xia et al., 2013; Younger et al., 2008). The value of walking, cycling and public transport is emphasized by a recent close review of the options to reduce emissions from transport sector. Creutzig et al. conclude that greater fuel and energy efficiency will not be sufficient to make the cuts necessary to hold warming to 2 °C by the end of this century: there will also need to be a reduction in transport demand (Creutzig et al., 2015). Increasing mode share for cycling and walking in place of private motor vehicles, either for whole or part journeys, generates health co-benefits from improved air quality and increased physical activity, though moderated in some cases by an increase in the risk of injury (Creutzig et al., 2015; Maizlish et al., 2017; Patz et al., 2008; Rissel, 2009; Xia et al., 2013, 2015). Kwan et al. indicated that the introduction of two new mass rapid transit lines in Greater Kuala Lumpur, Malaysia could reduce 337,800 tonnes of CO₂-equivalent per year from private transportation, while increased walking would prevent 90 deaths and 3200 DALYs (Kwan et al., 2017). Besides, active travel may increase social contact and the opportunity to interact with natural environments, as well as boosting physical activity in relatively sedentary populations, and reducing the risk of a range of chronic diseases such as cardiovascular disease, type 2 diabetes, colon and breast cancer, and depression (Haines et al., 2009; Rissel, 2009; Whitmee et al., 2015; Xia et al., 2013; Younger et al., 2008). However, in many developing countries, car use is increasing rapidly, and there is a rapid shift away from active travel (Michaelowa and Dransfeld, 2008; Quam et al., 2017). Therefore, policies and measures including well-designed urban public transport systems, safe urban environments for mass active travel, infrastructure investment priorities (e.g., cycling lanes), and prioritization of the needs of pedestrians and cyclists, are urgently needed to improve local air quality, reduce GHG emissions, and protect public health (Kwan et al., 2017; Patz et al., 2008; Watts et al., 2015; Woodcock et al., 2009).

2.3. Food and agriculture

According to the IPCC, agriculture is responsible for about 10–12% of global GHG emissions, and emissions from this sector are projected to increase by up to 50% by 2030 (Smith et al., 2007). Moreover, agriculturally-induced changes in land use, such as deforestation and overgrazing, contribute to a further 6–17% of global emissions (Bellarby et al., 2008). In order to respond effectively to these challenges of GHG emissions from agriculture sector, the following key points should also be kept in mind. First, livestock production, including energy and fertilizer use for growing grains for animal feed, CH₄ produced by the digestive processes of ruminant animals, and transport of animal products for processing and sale, are major sources of GHG emissions and account for about 80% of all agricultural emissions (Steinfeld et al., 2006; McMichael et al., 2007; Younger et al., 2008). Second, almost half of all food-related GHG emissions are generated during farming, including CH₄ emissions from livestock, N₂O from pasture and arable land used to

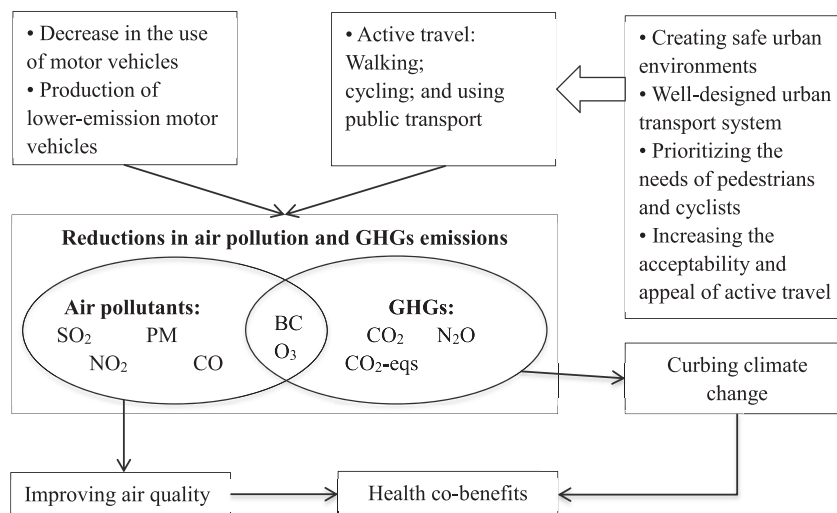


Fig. 5. GHG mitigation strategies and the related health co-benefits in transport system.

grow feed crops, and CO₂ from agriculturally-induced changes in land use, especially deforestation (Steinfeld et al., 2006; Friel et al., 2009; Reisinger and Clark, 2018). The expansion of agriculture has accelerated forest clearance in recent decades, particularly for livestock production and dairy farming. For instance, it is reported that 70% of once-forested land in the Amazon is now used for pasture and feed crops (Steinfeld et al., 2006). Third, a limited number of studies have investigated the effects on GHG mitigation of eating local, seasonal or sustainable food, but the findings are tentative and inconsistent (Biesbroek et al., 2014; Edwards-Jones, 2010; Macdiarmid, 2013, 2014; Springmann et al., 2016). This area of research requires further development to figure out the real associations and contributions of these factors.

High consumption of foods from animal sources not only leads to increasing risks of non-communicable diseases, such as type 2 diabetes, ischaemic heart disease and the prevalence of obesity, but also contributes to higher GHG emissions (Friel et al., 2009; Garnett, 2008; Kelly et al., 2017; Macdiarmid, 2013). Thus, there are opportunities for changes in the production and consumption of food that bring gains for both the environment and public health. For instance, improvements in agricultural technology and reductions in per capita consumption of foods from animal sources in current high-consumption areas. A study from Italy reported that hypothetical meat reduction scenarios according to the Mediterranean pyramid targets could save 8000–14000 Gg CO₂-eq per year, and would result in a 1.2%–6.0% reduction in mortality from colorectal cancer and between 1.2% and 5.2% from cardiovascular disease (Farchi et al., 2017). Other examples of response measures across the whole agricultural system from governments, producers and retailers to consumers include improving the efficiency of livestock farming (Friel et al., 2009; Younger et al., 2008), greater carbon capture and sequestration through optimal land use practices (Bustamante et al., 2014; Caldwell et al., 2007), and changing diets to favor less emission-intensive and lower-fat foods, at least for adult populations in high-income countries (Fig. 6) (Cederberg et al., 2013; Haines et al., 2009; Macdiarmid et al., 2012; McMichael et al., 2007; Quam et al., 2017). Besides, since local foods are usually responsible for releasing fewer GHG than the non-local, greater food miles are meaning higher levels of emissions for food items (Edwards-Jones, 2010), and transportation GHG emissions are sensitive to distances travelled (Thambiran and Diab, 2011), interventions that reduce the distances that food products are transported and improving the quality and range of locally

produced foods (Younger et al., 2008) are likely to ease the burden of food production on air pollutants emissions, yield health co-benefits and help to achieve the targets of GHG mitigation, at both global and national levels (Aleksandrowicz et al., 2016).

2.4. Residential and household sector

Although they include only 4.3% of the global population, the United States' households alone, directly or indirectly, are account for approximately 20% of global total GHG emissions per year (Jones and Kammen, 2014; Weber and Matthews, 2008). In the UK, energy use in residential buildings is responsible for about 140 megatonnes of CO₂ emissions per year, which is equivalent to around 26% of the country's total emissions (Wilkinson et al., 2009). In 2008, according to the IEA, residential buildings were estimated to account directly for almost 18% of global CO₂ emissions, with 11% from home use of grid-electricity and district heating, and the remainder arising from household-level heating and cooking with fossil fuels (biomass was not included) (Dora et al., 2011). In high-income countries such as the UK and the USA, greenhouse pollutants are mainly from the high energy use of electricity, air conditioning and heating (Haines et al., 2009). In the poorest communities of the world, the situation is contrasting. The poorest half of the world's households cooking, heating and lighting mainly with solid fuels, such as biomass or coal, which is responsible for close to 10% of global energy use (Goldemberg et al., 2004; Smith and Haigler, 2008). Altogether, about 7% of global energy use is attributed to residential use of wood fuels, associated in some locations with unsustainable harvesting of forests, leading to deforestation and consequent negative effects on uptake of atmospheric CO₂ (Anenberg et al., 2013; Mitigation, 2011). Thus, taking into account all these pathways, the household sector may make a larger contribution than currently recognized to global GHG emissions.

Household air pollution derived from cooking and space heating is associated with nearly 3.5 million premature deaths or 4.4% of the global burden of disease annually, predominantly in women and children in developing nations, and indoor air pollution is now listed as one of the main environmental causes of ill-health worldwide (Lim et al., 2013; Vardoulakis et al., 2015; Wilkinson et al., 2009). In the absence of systematic changes in urban and rural fuel-use patterns in sub-Saharan Africa between 2000 and 2030, it was estimated that household biomass use will lead to

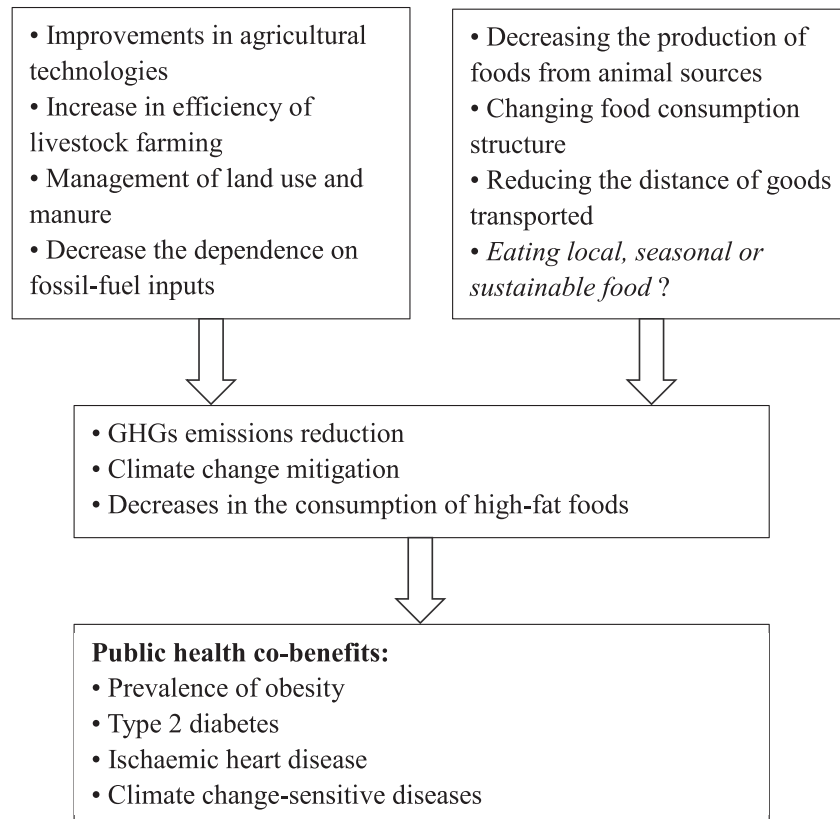


Fig. 6. GHG abatement strategies and the companion health co-benefits in food and agriculture sector.

about 8.1 million deaths from lower respiratory infections among young children, and 1.7 million deaths due to chronic obstructive pulmonary disease in adult women (Bailis et al., 2005).

Accordingly, there is potential in the residential and household sector to take steps to curb climate change and gain health benefits, and some of these win-win measures have been shown or modeled to be cost effective (Dora et al., 2011; Pachauri et al., 2014b; Wilkinson et al., 2009). For rich countries, given the complexities of the challenges, although mitigation strategies are usually focus on reductions in household energy use and improvements in energy efficiency through advance in fabrics, fuel switching and behavioral changes, no single intervention will be sufficient. For UK housing, for instance, depending on how housing interventions (energy efficiency measures) are implemented and maintained, the magnitude and even direction of effects on human health may discrepant, while the comprehensive strategy combined building fabric, ventilation, fuel switching and behavioral changes results in the greatest co-benefits, bringing about a savings of 0.6 MT of CO₂ and 850 fewer DALYs per million people per year, with respect to the 2010 baseline scenario (Wilkinson et al., 2009). However, increased airtightness of dwellings in pursuit of energy efficiency could also have negative effects on indoor air quality and lead to biological contamination. Therefore, adequate ventilation (e.g., mechanical ventilation with heat recovery and air filtration) needs to be provided in buildings (Vardoulakis et al., 2015). For low-income countries, household interventions, such as improvements in the combustion efficiency of household solid fuels (Dora et al., 2011), promotion in modern low-emissions appliances and substitution of traditional cooking and space heating practices with clean household fuel technologies and lower-emission stoves (Ochieng et al., 2013; Venkataraman et al., 2010; Wilkinson et al., 2009), if designed and implemented properly, could bring cost-beneficial

health gains in addition to reductions in GHG emissions. A study from India estimated that if measures were fully implemented in 2005, initiatives to develop low-emission biomass cook stoves and disseminate them to households currently used traditional cook stoves would save 80 MT of CO₂-eq per year and averted approximately 570,000 premature deaths of poor women and children due to decrease in air pollution (Venkataraman et al., 2010). Given the fact that about 41% of the global households depending on solid fuels for cooking are concentrated among the poor in developing societies (Bonjour et al., 2013; Pachauri et al., 2014a), approaches like providing affordable and reliable low-emission stoves and clean cooking energy options for poor households in countries where indoor air pollution is most severe (Haines et al., 2009; Venkataraman et al., 2010) may also offer potential game-changing opportunities to achieve simultaneous benefits in health and welfare for vulnerable populations, especially children and women, while achieving GHG mitigation at the local level (Fig. 7) (Anenberg et al., 2013; Dora et al., 2011; Wilkinson et al., 2009).

2.5. Industrial and economic processes

The industrial sector is the largest energy consumer worldwide, exceeding the footprint of transport systems (30%) (Atabani et al., 2011; Watts et al., 2017a), and comparable in global GHG emissions with the agriculture sector (McMichael et al., 2007). In addition, industrial and economic processes release harmful air pollutants such as PM, NO_x, SO₂ and BC, which have direct impacts on public health. For example, in 2012, a study from the UK estimated that industrial combustion emissions result in about 830 early deaths per year (Yim and Barrett, 2012). Accordingly, for the industrial and economic sectors, health co-benefits could be expected of GHG mitigation from reductions in air pollutants

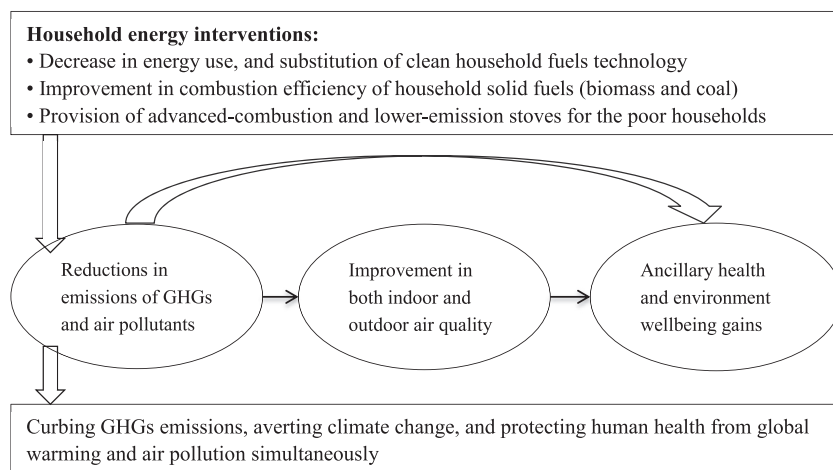


Fig. 7. GHG mitigation measures and the corresponding ancillary health benefits in household sector.

achieved through a variety of measures, including shifting away from fossil fuel energy sources (Thambiran and Diab, 2011), improving energy efficiency (Liu et al., 2013; Shrestha and Shakya, 2012), adjusting industrial and energy structures (He et al., 2010; Ma et al., 2013; Wu et al., 2015), promoting the application of clean and renewable energy (Scipioni et al., 2012; Zhai et al., 2011), increasing investments in low carbon technologies and developing low carbon economies (Aunan et al., 2004; Ren et al., 2012), and implementing clean development mechanism, particularly in rapidly developing countries (Aunan et al., 2006; Vennemo et al., 2006). All of these policies, if properly implemented and coordinated, may create synergies for addressing the challenges posed by climate change, air pollution and the related public health risks (Fig. 8). For example, the hypothetical climate change mitigation policy scenarios in Mexico that a 77% CO₂ emissions reduction throughout the Mexican economy could avoid 2718 premature deaths, because of the accompanying reductions in ozone and PM concentrations relative to the BAU scenario (Crawford-Brown et al., 2012).

2.6. Short-lived climate pollutants, mitigation measures and health co-benefits involving various economic sectors

It has been suggested that when assessing the benefits of GHG mitigation measures, if only the beneficial implications of CO₂ controls are considered while ignoring the benefits from decreases in CH₄ and other GHGs emissions, the evaluation may underestimate the overall effects and provide inadequate information to decision makers and other stakeholders (Marten et al., 2015). Although CO₂ is the primary anthropogenic GHG, other GHGs or CO₂-eqs such as CH₄, BC and N₂O are also important contributors to climate change (International Energy Agency, 2015; Edenhofer et al., 2014a; World Health Organization, 2015; Stocker et al., 2013). For instance, in 2011, while the atmospheric CO₂ concentration accounted for 64% of overall RF, CH₄ and N₂O contributed approximately 23% (Myhre et al., 2013; Pachauri et al., 2014a; Smith et al., 2009). Moreover, it is estimated that the emissions of anthropogenic CH₄ have led global atmospheric CH₄ concentrations to more than double since the pre-industrial period, causing a positive RF that is second only to CO₂ (Forster et al., 2007). In addition to being a GHG, CH₄ is an O₃ precursor that affects atmospheric background O₃ concentrations. Like BC, O₃ is also a climate warming agent and degrades air quality (World Health Organization, 2015; West et al., 2012). CH₄ also has an indirect

impact (through O₃) on premature mortality and losses in crop yields (Forster et al., 2007; Scovronick et al., 2015; Shindell et al., 2012; Watts et al., 2017b).

Studies have shown that controlling short-lived climate pollutants such as CH₄ and BC, together with a reduction in CO₂ emissions, could increase the chances of slowing down climate change and keeping the global temperature rise below the UNFCCC suggested 2 °C (Anenberg et al., 2013; World Health Organization, 2015; United Nations Environment Programme, 2011), while bringing large benefits for air quality, agriculture and public health (Scovronick et al., 2015; Shindell et al., 2012; West et al., 2006). Moreover, because anthropogenic CH₄ and BC are short-lived (for CH₄, the residence time is 8–10 years) relative to the long-lived GHGs (e.g., CO₂), these benefits would be achieved in the near-term and on a local scale (Scovronick et al., 2015; Smith et al., 2009; West et al., 2007). Therefore, mitigation of short-lived climate pollutants provides an attractive opportunity to avert climate change and improve public health simultaneously, and can also be a cost-saving component of both international and regional air pollution control (Marten et al., 2015; World Health Organization, 2015; West et al., 2006, 2012).

Tropospheric BC is one of only two agents (the other is ozone) known to contribute strongly both to climate warming and ground-level air pollution (Shindell et al., 2012). BC is a component of PM_{2.5} produced mainly by incomplete combustion of fuels (Bond et al., 2013; Field et al., 2014; Gao et al., 2017a). Globally, about 93% of anthropogenic BC is emitted from residential, industrial and transportation sources (Anenberg et al., 2011; Molina et al., 2009), accompanied by other co-emitted pollutants, including NO_x, CO, SO₂ and organic carbon (Anenberg et al., 2012; Scovronick et al., 2015). The contribution of each sector to BC emissions varies in different regions. In China, for instance, 50% and 35% of total BC derives from the industrial and residential sectors, respectively (Anenberg et al., 2012). As a component of PM_{2.5}, BC decreases atmospheric visibility, contaminates the surfaces of buildings, and imposes adverse effects on human health when inhaled by penetrating deeply into the lungs (Gao et al., 2017a; Kopp and Mauzerall, 2010; Krewski et al., 2009; Nel, 2005). Besides, BC may contribute to global warming by absorbing solar radiation, decreasing the appearance albedo of snow and ice, and influencing cloud lifetime and reflectivity to amplify warming effects indirectly (Flanner et al., 2009; Koch and Del Genio, 2010; Molina et al., 2009; Scovronick et al., 2015; Stocker et al., 2013).

It has been estimated that BC emissions could be halved by 2030

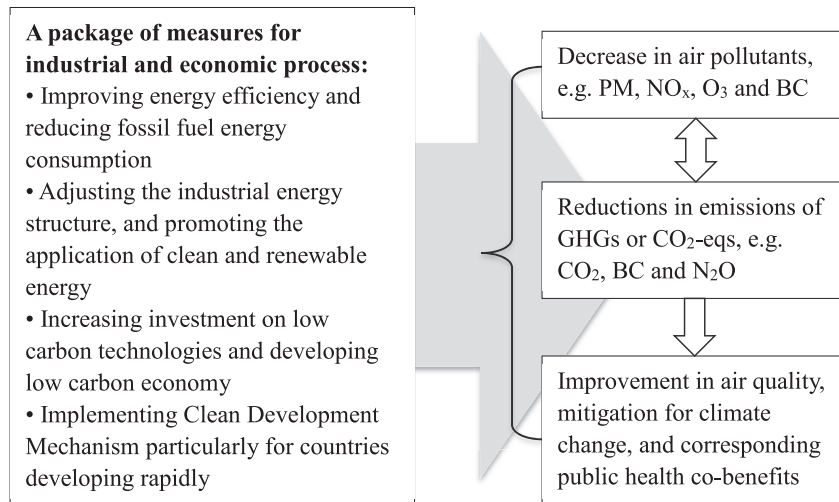


Fig. 8. GHG mitigation actions and potential health co-benefits during industrial and economic process.

if current combined control technologies were fully implemented (Cofala et al., 2007); and a 50% reduction in BC emission would be sufficient to offset the warming effects of one to two decades of CO₂ emissions (Wallack and Ramanathan, 2009). Since BC remains in the atmosphere (lifetime) for no more than days to weeks, reductions in BC emissions would lead to a more immediate and direct climate and health response than would be achieved by a cut in CO₂ emissions, which further serves as a fertile area for cooperation and co-action between developed and developing countries during global climate diplomacy and negotiations (Bice et al., 2009; Kopp and Mauzerall, 2010; World Health Organization, 2015; Scovronick et al., 2015; Watts et al., 2015). Anenberg et al. estimated the counterfactual abatement policy scenario that halving anthropogenic BC emissions in eight world regions and three major economic sectors could avert 157,000 (95% CI: 120,000–194,000) premature deaths annually around the world, due to the accompanied PM_{2.5} emissions reduction (Anenberg et al., 2011). Although the net climate benefits of BC decrease may be partially offset by associated reductions in co-emitted pollutants that have a cooling effect on climate (Anenberg et al., 2012; Smith et al., 2009), if the faster health gains that result from reductions in PM_{2.5} and other combustion-related pollutants (e.g., NO_x and CO) because of the whole emission reductions are considered, BC reductions overall provide ample cost-beneficial opportunities to address near-term climate warming and air pollution simultaneously (Anenberg et al., 2011, 2013; Scovronick et al., 2015; Smith et al., 2009).

Anthropogenic CH₄ sources are found in various sectors such as energy generation, agriculture and food production (especially livestock), and waste treatment, so mitigation actions aiming to control CH₄ emissions through comprehensive strategies involving multiple sectors are needed (Anenberg et al., 2012; Shindell et al., 2012; Watts et al., 2015; West et al., 2012). These integrated strategies can simultaneously reduce the negative impacts of air pollution and climate change, especially when the GHGs and air pollutants are co-generated by the same sources (Fig. 3) (Chae and Park, 2011; World Health Organization, 2015; Rive and Anan, 2010; Scovronick et al., 2015; Wilkinson et al., 2009). West et al. investigated the health co-benefits of modeled CH₄ mitigation scenarios involving different economic sectors (e.g. energy, industry and agriculture) from a global perspective, and indicated that 19,500–57,200 premature deaths could be prevented in 2030 (West et al., 2012). Given that developing countries are currently responsible for around two-fifths of global CO₂ emissions, more

than half of N₂O emissions, and approximately two-thirds of CH₄ emissions, and considering the co-location of major sources of GHG emissions and dense urban populations, the creation of optimized and integrated strategies to address air pollution and climate change is particularly crucial for mega cities in developing nations that are dealing with both air pollution and climate change with limited economic resources (Anenberg et al., 2011; Chae, 2010; Ma et al., 2013; McMichael et al., 2007; Swanson et al., 2014).

2.7. Others

Another mitigation measure that needs further attention is urban green space. On one hand, the potential benefits of carbon capture and sequestration resulting from afforestation and reforestation programs have been identified in several studies, with scientific evidence generally suggesting that forests can play a significant role as atmospheric CO₂ sinks through absorbing and fixing CO₂ from the atmosphere (Bustamante et al., 2014; Caldwell et al., 2007; Wang and Lin, 2012). Thus, afforestation and reforestation have been considered as important means to remove CO₂ from the atmosphere (Salwasser, 2006; Whitmee et al., 2015). On the other hand, urban green space could bring health gains through multiple pathways, such as improving air quality, mitigating the urban heat island effect, providing opportunities for flood risk management, enhancing cultural and aesthetic values (Salmond et al., 2016; Tiwary et al., 2009), offering restorative experiences, stimulating physical activity, and increasing social contact and neighborhood cohesion, which can result in stress reduction, recovery from attentional fatigue, decreases in obesity-related diseases, and improvements in mental health (de Vries, 2010; De Vries et al., 2011; Hartig et al., 2011; Van den Berg et al., 2010; Van Dillen et al., 2012). For instance, a systematic review of health benefits of exposure to natural environments suggested that significantly lower levels of negative emotions, such as anger and sadness, were experienced after contact with the natural environment (e.g., public parks and green university campuses) in comparison with a more synthetic environment (Bowler et al., 2010b). A number of studies have suggested that urban green spaces could offer appreciable climate-health links with respect to potential GHG mitigation co-benefits (Bustamante et al., 2014; Shannon et al., 2007; Wang and Lin, 2012; Watts et al., 2015). However, the aforementioned benefits of green space can vary with setting, vegetation species, canopy design and region. Besides, there is no

study that has fully quantified the associations between GHG reductions that result from increased urban green space and the corresponding health gains, which suggests that further research is needed (Campbell et al., 2012; Lee and Maheswaran, 2011; Van den Berg et al., 2010; Van Dillen et al., 2012; Younger et al., 2008).

3. Knowledge gaps

Based on the review of current literature involving GHG emissions, mitigation strategies and related health co-benefits, several knowledge gaps were identified. First, according to the present review, to date there is little evidence in the scientific literature of cost-effectiveness analysis, in practice, of the health-promoting interventions to reduce GHG emissions. Most of the studies are descriptive or modeling investigations, and a noteworthy gap in the scientific research on the health co-benefits of GHG mitigation is the lack of intervention studies and assessments based on actual surveillance data (Pachauri et al., 2014b; Remais et al., 2014). Second, compare with conventional assessment approaches, there are some fundamental sources of uncertainties that characterize the key steps of the model studies of the health co-benefits associated with GHG abatement (Haines et al., 2009; Remais et al., 2014). The data quality and availability, the exposure–response parameters for health outcomes, the variation in air pollutant mixtures and the toxicity around the world, and the worldwide different population, environment and medical care infrastructure characteristics, are all encumbered with uncertainties, presenting underestimation or overestimation, which make the full range health co-benefits assessment of GHG emissions reduction challengeable (Gao et al., 2018; Patz et al., 2014; Watts et al., 2015). Third, although several studies have attempted to model or quantify the associations between GHG emissions reduction and health co-benefits, few studies have tried to establish a thorough performance appraisal system for the evaluation of environmental, socioeconomic and public health co-benefits in relation to GHG mitigation measures (Haines et al., 2009; Pachauri et al., 2014a; Smith et al., 2014). It has been indicated that an integrated performance appraisal system including pre-implementation analyses of interventions, and follow-up cost–benefit appraisals of program implementation and related results, is crucial to assess comprehensively the performance of specific GHG abatement strategies, and could help enhance the efficiency of decision-making processes and help programs to compare and prioritize potential options (Chae and Park, 2011; McMichael et al., 2012; Rojas-Rueda et al., 2011). To date, cost-effectiveness analysis has been mainly conducted for limited intervention studies based on existing available data that reducing GHG emissions from electricity and household stoves (Gao et al., 2018). However, some issues have been raised during the assessments, including poor data quality and availability, ethical problem when take different values for the health benefits (reductions in premature mortality) dependent on how wealthy a country or region is, various magnitude of the health benefits that should be traded against costs of policy implementation, not all health co-benefits can be quantified, and the monetary values only represent a part of the full set of health gains, which challenge the cost-effectiveness analysis to be done extensively (Gao et al., 2018; Haines et al., 2009; Patz et al., 2014; Remais et al., 2014).

In addition, to date, most of the health benefit assessments have been performed in developed societies, with insufficient research having been carried out in developing regions, especially in areas like Africa and Asia, where the least GHG emissions are generated while the most severe climate change consequences are suffered (Organization for Economic Co-operation and Development, 2015; Haines et al., 2009; World Health Organization, 2012; Pachauri et al., 2014a; Patz et al., 2008; Smith et al., 2014). These already

susceptible areas, affected by conflicts, unstable politics and impaired water supplies, as well as poor health infrastructure and limited economic resources, may become more vulnerable due to further climate change and the projected increasing frequency and intensity of extreme weather events (Organization for Economic Co-operation and Development, 2015; Barros et al., 2014; Kreft et al., 2016; Pachauri et al., 2014a; Shindell et al., 2012; West et al., 2012; Whitmee et al., 2015). Finally, despite the potential health benefits of urban green space having been suggested by some studies (Bowler et al., 2010a; Lee and Maheswaran, 2011; Salmond et al., 2016), the quantitative relationships between GHG emissions reduction associated with green space and human health gains have not been fully evaluated. In order to take advantage of the public health opportunities offered by climate change mitigation measures (Wang and Horton, 2015; Watts et al., 2015), all of these areas for future research need to be explored.

4. Policy implications

To date, although health co-benefits of GHG mitigation strategies in different sectors have been modeled or quantified to a certain extent, their potential to provide cost-beneficial solutions has not been widely recognized, especially in developing nations, and this may hamper international cooperation for further global GHG emissions reduction (Nemet et al., 2010; Pachauri et al., 2014b; Watts et al., 2015, 2017b). Therefore, promoting education and raising awareness on this topic for policy-makers, health professionals and other stakeholders is crucially needed, particularly in countries and regions confronted with multiple challenges from development, urbanization, growing population, air pollution and climate change (Haines et al., 2009; Jiang et al., 2013; Walsh, 2008). If the public health co-benefits of GHG reductions were more widely recognized, this would provide an opportunity to help break the present impasse in international climate negotiation, rethink the necessity of global coordination and co-action in GHG mitigation, facilitate the development and implementation of more ambitious climate change mitigation policies, and motivate low carbon transition and green growth in both developing and developed countries around the world (de Oliveira et al., 2013; Edenhofer et al., 2014a; Gao et al., 2018; Heitzig et al., 2011; Patz et al., 2014).

Given the complexities of the challenges posed by climate change, major medical associations and non-governmental health organizations have been calling for integrated multisectoral and multidisciplinary policies and actions to protect human health from dangerous climate change (Edenhofer et al., 2014b; Haines et al., 2009; Lim et al., 2009). The existing evidence has suggested that comprehensive mitigation strategies generally provide greater health gains and higher GHG reductions (Anenberg et al., 2012; Friel et al., 2009; Sabel et al., 2016; Shindell et al., 2012; West et al., 2012; Woodcock et al., 2009). Thus, interdisciplinary mitigation frameworks linking the energy generation, transport, agriculture, household and industry processes are essential for curbing GHG emissions and improving public health simultaneously.

For developing settings like countries in the Asia and Africa, they are usually the highly populated regions (Shindell et al., 2012); have the highest baseline mortality rates in the world (West et al., 2012); populations are vulnerable because of impaired food and water supplies, poor nutrition and health infrastructure, and access to health care (Haines et al., 2009; Watts et al., 2015; Whitmee et al., 2015); relying mainly on inefficient combustion of solid household fuels (Venkataraman et al., 2010; Wilkinson et al., 2009); populations are exposed to higher air pollution level than the national or international agencies suggested health-protection values (Anenberg et al., 2011; West et al., 2013); air quality policies and

regulations to limit pollutants emissions are lacking or unenforced (Patz et al., 2014; Rafaj et al., 2013); Existing health disparities are being further exacerbated by climate change, ecosystem disruption and extreme weather events (Barros et al., 2014; Whitmee et al., 2015). Therefore, it is not surprise that existing studies generally suggest that both climate and health benefits are typically greater in developing countries, despite the potential that health benefits per unit reduction in PM and precursors emissions would be higher in cleaner settings like high-income nations in Europe and North America, according to the PM_{2.5} integrated exposure-response curves, with higher social and healthcare resources investments and lower public health and welfare gains (Gao et al., 2018; Haines et al., 2009; Kelly et al., 2017; Quam et al., 2017; Watts et al., 2017b; Whitmee et al., 2015).

Although the scientific literature has indicated that health co-benefits can greatly offset the costs of GHG mitigation actions (Markandya et al., 2009; Watts et al., 2015; Wilkinson et al., 2009), in some countries climate change mitigation is still considered as an issue that conflicts with the goals of economic and social development (Edenhofer et al., 2014a; Lim et al., 2009; Rafaj et al., 2013). However, we argue that in order to work toward the target of GHG mitigation, joint actions and collaborations not only from different governmental departments at national level, but also between high- and low-income countries at international level are crucially required (Edenhofer et al., 2014b; Pachauri et al., 2014a; Smith et al., 2009; Watts et al., 2015; Whitmee et al., 2015). Hence, in addition to research and awareness raising, financial and technological assistance from industrialized countries to developing nations and international collaboration in knowledge transfer and capacity building are needed (Anenberg et al., 2013; Field et al., 2014; Haines et al., 2010; Watts et al., 2015). The potential health co-benefits of GHG abatement could further increase the motivation of low-income nations to make decisive changes when balancing environmental and public health concerns against economic growth (Field et al., 2014; Haines et al., 2009; Watts et al., 2017a; Whitmee et al., 2015; Xu and Masui, 2009).

In addition, studies have suggested that health professionals could play an important role in combating climate change and GHG emissions. For instance, they could advocate for comprehensive local, national and international policies to reduce GHG emissions and achieve health co-benefits (Haines et al., 2009, 2010). Health and environment professionals can also serve as a role model for practices in their own workplace, community and even region, to help inform and educate the local and national public and policy-makers about the health risks posed by climate change and the health co-benefits of GHG mitigation (Shannon et al., 2007; Watts, 2009; Watts et al., 2015, 2017b). They should also be encouraged to reach beyond conventional professional boundaries to work with regional and state health authorities to promote the development and implementation of mitigation strategies (Haines et al., 2009; Woodward, 2015).

Although numerous studies have focused on the role of governments and economic sectors in mitigating climate change, relatively limited attention has been paid on the effects of individual behavior change on GHG reductions, during both scientific research and public policy making (Gao et al., 2017b; Macdiarmid, 2013; Watts et al., 2015; Xia et al., 2013). In terms of the co-benefits resulting from behavior changes, such as shifting car trips toward active travel, limiting consumption of foods from animal sources, using lower-emission stoves and reducing energy use, the collective impact of small behavior changes may result in a considerable increase in health gains and reduction in GHG emissions (Friel et al., 2009; Haines et al., 2009; Hendrie et al., 2014; Venkataraman et al., 2010; Xia et al., 2015). It is plausible that reframing climate change mitigation policies from a public health viewpoint and linking GHG

abatement actions to beneficial health gains (positive vision) could encouraging public engagement in mitigative behavior change (Gao et al., 2018; Watts et al., 2015). In light of government agencies and non-governmental organizations are increasingly encouraging individuals to “do their bit” in the battle with global warming, the “down to earth” and personally-relevant health co-benefits of GHG mitigation measures may play a more persuasive role in this process (Gao et al., 2017b; Reynolds, 2010; Wynes and Nicholas, 2017).

5. Conclusion

In the present paper, we summarized the available evidence on GHG emissions, mitigation strategies and the corresponding health co-benefits, mainly involving five sectors: energy generation, transport, food and agriculture, household, and industry and economy. The pros and cons of different mitigation measures, issues with existing knowledge, future priorities for research, and potential policy implications were also discussed. According to our knowledge, this is the first comprehensive review of GHG emissions and related mitigation measures from health perspective. Findings from this study will, it is hoped, shed light on the existing knowledge gaps related to the topic of GHG abatement, and provide necessary evidence for the further development and implementation of mitigation policies in both developing and developed countries. The anticipated cost-effective health co-benefits produced by GHG abatement measures could make climate change mitigation policies more appealing and true “no-regrets” options for policy-makers and GHG emitters, especially in low-income countries with finite economic resources. Findings of the present study may play a role not only in motivating large GHG emitters to make voluntary and decisive changes that would help reduce emissions, while prioritizing mitigation measures with optimal health gains, but also in facilitating cooperation and co-action at international, national and regional levels, based on traditional situations, social expectations and actual resource availability to protect human health from dangerous climate change and air pollution simultaneously.

Conflicts of interest

The authors all declare they have no actual or potential competing financial interests.

Authors' contributions

JHG and QYL conceptualized, designed and initiated the study. JHG and QYL drafted the initial manuscript. LX, BHM, XBL and JW involved in the development of methodology and discussion of article structure, AW, SV, SK, PW, LPL, XQS, HLH, YKZ, JZ and QYL reviewed and revised the manuscript. All authors read and approved the final manuscript as submitted.

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